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# Contribution of vertebral bodies, endplates, and intervertebral discs to the compression creep of spinal motion segments

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## Abstract

Spinal segments show non-linear behavior under axial compression. It is unclear to what extent this behavior is attributable to the different components of the segment. In this study, we quantified the separate contributions of vertebral bodies and intervertebral discs to creep of a segment. Secondly, we investigated the contribution of bone and osteochondral endplate (endplates including cartilage) to the deformation of the vertebral body.

From eight porcine spines a motion segment, a disc and a vertebral body were dissected and subjected to mechanical testing. In an additional test, cylindrical samples, machined from the lowest thoracic vertebrae of 11 porcine spines, were used to compare the deformation of vertebral bone and endplate. All specimens were subjected to three loading cycles, each comprising a loading phase (2.0 MPa, 15 min) and a recovery phase (0.001 MPa, 30 min).

All specimens displayed substantial time-dependent height changes. Average creep was the largest in motion segments and smallest in vertebral bodies. Bone samples with endplates displayed substantially more creep than samples without. In the early phase, behavior of the vertebra was similar to that of the disc. Visco-elastic deformation of the endplate therefore appeared dominant. In the late creep phase, behavior of the segment was similar to that of isolated discs, suggesting that in this phase the disc dominated creep behavior, possibly by fluid flow from the nucleus.

We conclude that creep deformation of vertebral bodies contributes substantially to creep of motion segments and that within a vertebral body endplates play a major role.

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**Keywords:** Creep; Spine; Intervertebral disc; Endplate; Mechanical testing

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## 1. Introduction

The main function of the intervertebral disc is to confer flexibility to the spine, while transferring the external load from one vertebral body to the next. Gravity and, in particular, muscle forces cause loading on the spine (Wilke et al., 1999; Nachemson and Morris, 1964). The load on a vertebral body is mainly axial compression, which runs from one endplate to the next (Horst and Brinckmann,

1981; Smit et al., 1997). Compression forces of every-day activities are large enough to cause damage to the spine, and are therefore thought to be an important cause of low back pain (van Dieen et al., 1999).

The response of a segment to compression loading is non-linear (Panjabi et al., 1994; Kaigle et al., 1997). This is attributed to the non-linearity of the material properties and to the complex structure of the segment.

The smallest functional unit of a spine is a motion segment. A motion segment consists of an intervertebral disc with two adjacent vertebral bodies; the intervertebral disc is the most flexible part of a motion segment.

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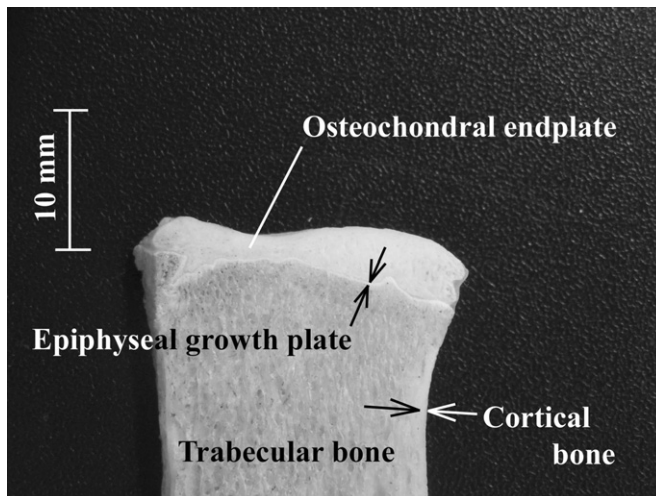


Fig. 1. Sagittal cross-section of a vertebral body showing a detail of the endplate region (the tested sample contained both endplates). The thickness of the endplate varies over the disc. Note that the epiphyseal growth plate is hardly distinguishable due its limited height.

The intervertebral disc comprises of a layered annulus with a gelatinous nucleus in its center, bound by the endplates. The vertebral body supports the endplate (Fig. 1). The endplate consists of a perforated plate of bone and a layer of hyaline cartilage (Roberts et al., 1989). Below the endplate an epiphyseal growth plate is present in young individuals (Albert and Maples, 1995). In the present paper, we refer to this whole complex on top of the trabecular bone of the vertebral body, including epiphyseal growth plate, cortical bone and the layer of hyaline cartilage, as the endplate.

The nucleus can be considered incompressible (Keyes and Compere, 1932). Consequently, when a segment is compressed, the annulus bulges outward (Reuber et al., 1982), but also the endplate bulges into the vertebral body (Roaf, 1960; Rolander and Blair, 1975; Brinckmann et al., 1983). The endplate is supported by cortical bone at the edge and by trabecular bone in the center. The structural stiffness of this support, therefore, varies with the location on the endplate (Abe et al., 1996). Due to the large differences in structural and material properties of the intervertebral disc, endplate and vertebral body it is to be expected that the role of the vertebral body in the deformation of a segment under compression is limited. However, vertebral bodies were shown not to be infinitively stiff (Holmes et al., 1993; Holmes and Hukins, 1993). Hence, the contribution of the vertebral bodies to the deformation of a motion segment cannot be neglected. If vertebral bodies contribute significantly to the deformation of the segment, this has to be taken into account in mechanical testing and computer simulations (e.g. finite element models) that describe the behavior of the intervertebral disc.

This structural complexity is combined with non-linear material properties of the components. Several studies have investigated creep behavior of the separate parts of a

motion segment (Brinckmann et al., 1983, 1985; Setton et al., 1993; Iatridis et al., 1998; Holmes and Hukins, 1993). The materials of the disc exhibit both visco-elastic and poro-elastic behavior (Zilch et al., 1980; Koeller et al., 1984). Visco-elasticity means that the stress–strain relation of the solid material is time dependent (Li et al., 1995). Collagenous tissue, such as found in the annulus, shows time-dependent deformation probably as a consequence of the release of hydrogen and salt-like bonds between fibrils and matrix (Chu and Blatz, 1972). Poro-elasticity implies that fluid flow, into or out of the disc, plays a role in the mechanical behavior of the disc (Huyghe et al., 2003; Schroeder et al., 2006; van der Veen et al., 2006; Koeller et al., 1984). This behavior is time-dependent as well. In addition, bone shows non-linear and time-dependent material behavior (Lakes and Saha, 1980; Zilch et al., 1980; Yamamoto et al., 2006; Sedlin, 1965) and it can thus be expected that the vertebral body will show time-dependent deformation when compressed.

The influence of vertebral bodies on the deformation of motion segments of rodents was recently reported (Maclean et al., 2006). However, the separate contribution of the endplates to the deformation of a segment remains unclear, because in this study it was not possible to discriminate between the deformation of the endplate and the bone. The goal of the present study is to quantify the contribution of all the individual parts in a motion segment.

In the present study, porcine specimens were used. Compression tests were performed on single vertebral bodies, complete motion segments (including both outer endplates), isolated discs and the separate test on bone cylinders with and without endplates. This combination of results allows quantification of the effect of endplates on the creep of motion segments. We hypothesized that time-dependent deformation (creep) of the intervertebral disc, the endplates and bone all would contribute to the time-dependent deformation of the motion segment. Secondly, we hypothesized that the creep behavior of the endplate has a strong influence on the early creep of the motion segment.

## 2. Materials and methods

We performed two separate tests to quantify the creep behavior of a complete motion segment and its components.

In the first test, time-dependent mechanical behavior of motion segments (S), intervertebral discs (D) and vertebral bodies (V) was compared (Fig. 2). In the second test time-dependent behavior of cylindrical bone samples, before (E) and after (B) removal of the endplates, was compared (Fig. 2). The cylindrical samples were taken from the lowest thoracic vertebral bodies of 11 additional porcine spines.

### 2.1. Specimens

Lumbar spines (L1–L5) of eight, 10-month-old pigs were harvested and frozen for later usage. From each lumbar spine, one spinal motion segment (which was composed of a vertebra, a disc and a vertebra, including both outer endplates: S), one single vertebral body (including the

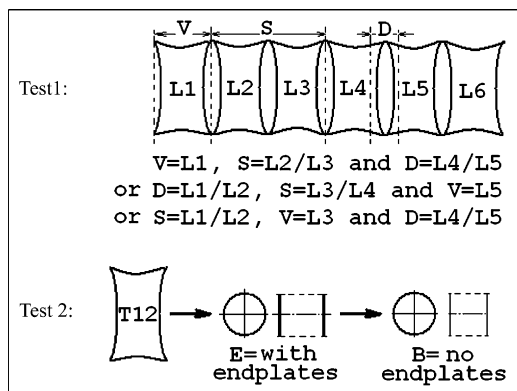


Fig. 2. Location of the tested samples in the spine. In the first test motion segments (S), intervertebral discs (D) and vertebral bodies (V) were compared. Segment, disc and vertebral body were taken from alternate locations of the spines. For the second test a sample was machined from the lowest thoracic vertebral body of an additional spine. The cylindrical sample was tested with both endplates attached (E) and tested after removal of the endplates (B).

endplates of the adjacent intervertebral discs: V) and one isolated intervertebral disc (including its adjacent endplates: D) were taken. Segment, disc and vertebral body were taken from alternate locations of each spine (Fig. 2). The posterior part of the spine was removed at the pedicles, to avoid load bearing by the facet joints. A scalpel was used to remove all soft tissue from the outer endplates of segment and vertebral bodies. Since the outer endplates of motion segments and vertebral bodies do not have flat surfaces, the endplates were embedded in aluminum cups to ensure a good interface with the testing device. The free space between cup and specimen was filled with a metal alloy (alloy: Cerrolow-136; melting point of 55 °C). Finally, the cups were attached to the material testing machine.

The intervertebral discs were cut from the spine by two parallel cuts using a band saw. The remaining layers of trabecular bone on the inferior and superior sides of the disc were cleaned with gauze, which was soaked in saline, and rinsed. The intervertebral disc specimens were placed between two porous plates during testing (porosity code 1, 100–160 µm pore size). This allowed fluid flow from the bath to the endplates and vice versa.

The second test was performed on cylindrical samples taken from the last thoracic vertebral body of the thoracolumbar transition of 11 porcine spines. From the center of the vertebral body of each vertebra, a 10 mm cylindrical sample was machined, i.e. a trabecular bone plug with both endplates, including the hyaline cartilage, still attached. In order to have a good interface with the testing device, a thin layer of bone cement was used to level the outer surface of the samples. After testing of the cylindrical samples with the endplates attached (E), the endplates were removed by two parallel cuts (B), using a band saw. The remaining sample consisted only of trabecular bone. Again a thin layer of bone cement was used to level the outer surface of the samples.

## 2.2. Mechanical tests

All samples were thawed at room temperature prior to testing. The specimens were tested in a saline bath at 37 °C.

For the test on motion segments, intervertebral discs and vertebral bodies a trace of the shape of the intervertebral disc was made on graph paper; the total area of each intervertebral disc was measured and used to calculate the required force to obtain a disc pressure of 2.0 MPa. This calculated load was applied to all samples from the same animal.

For the test on cylindrical samples, the area of the cross-section of the cylindrical samples was calculated and used to determine the required test force to obtain a pressure of 2.0 MPa. The same loading pattern was applied in both tests. Specimens were preloaded at 0.001 MPa for 15 min.

Subsequently, they were loaded with three complete loading cycles with a loading phase of 15 min at 2.0 MPa and a recovery phase of 30 min at 0.001 MPa. The repeated measurement allows assessment of non-recurrent deformation.

Compression tests were performed with a hydraulic mechanical testing device (Instron 8872, Canton, MA). Load and vertical displacement of the cross head of the Instron were recorded at a frequency of 2 Hz. The vertical displacement of the crosshead was equivalent to the height loss of the sample. The following dependent variables were calculated: height loss over each complete loading/unloading cycle, recovery of height during the unloading phases, the change of height during the interval from 2 to 60 s and during the final 10 min of each loading or unloading phase.

## 2.3. Statistics

A Student's *t*-test for paired-samples was used to compare the means of two groups. Where multiple comparisons were made (e.g. comparing motion segments, discs and vertebral bodies and the three loading cycles), Bonferroni correction was applied resulting in a significance level of  $\alpha = 0.0167$ .

## 3. Results

### 3.1. Test on motion segments, intervertebral discs and vertebral bodies

The deformation under compression (Fig. 3a) was time-dependent in all the three groups: motion segments (S), isolated discs (D) and vertebral bodies (V).

The change of specimen height was calculated with respect to the height at the end of the previous loading phase (Fig. 3b). In all samples, the loss of height was smaller during the second and third loading cycle than in the first cycle ( $p < 0.005$ ). The gain of specimen height during the unloading phases was almost invariant over the three cycles within each group.

The deformation rate decreased considerably over time during loading and unloading in all the three groups (Fig. 4). During the loading phase of the test, the first 2 s of the test protocol, the compression load was increased from 20 N to the required test load. After the loading phase the load was maintained at the maximum test level. The deformation of the motion segments was about twice that of both the single discs and vertebral bodies (Fig. 4,  $p < 0.001$ ). In the final 10 min of the loading phase the rate of deformation was clearly smaller in the vertebral bodies compared to motion segments and discs ( $p < 0.001$ ). A similar pattern was observed during the unloading phase. However, in the last 10 min of the unloading phase, height recovery was very small in all the three groups.

### 3.2. Test on cylindrical samples

The change of height of the vertebral body contributes substantially to the mechanical behavior of the motion segment, especially during the first minute of loading. To further differentiate between effects of the endplates and the vertebral body, bone cylinders with endplates (E) and without endplates (B) were compared. The length of the

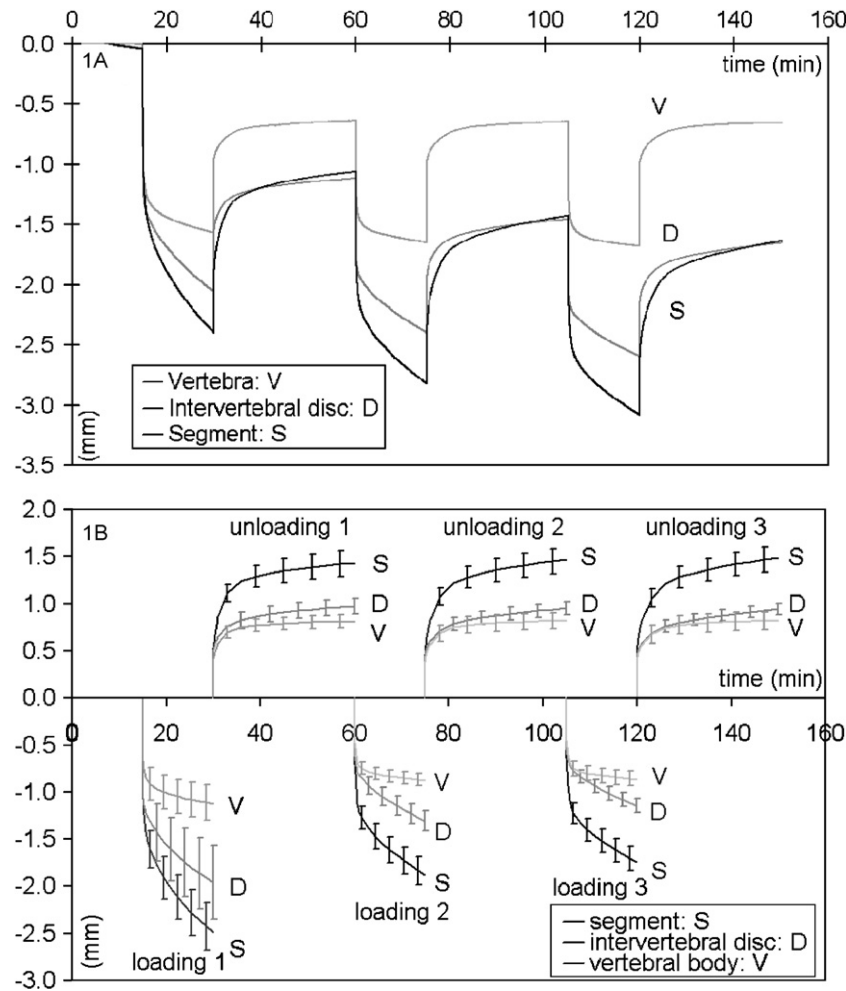


Fig. 3. (a) Typical example of a compression load applied to a motion segment, an intervertebral disc, and a vertebral body showing the height change during three loading cycles. All samples in this figure were obtained from the same animal. (b) Average changes in sample height of the motion segments, intervertebral discs and vertebral bodies in each loading and unloading phase. The change of height was calculated relative to the height at the end of the previous phase. Error bars indicate standard deviations.

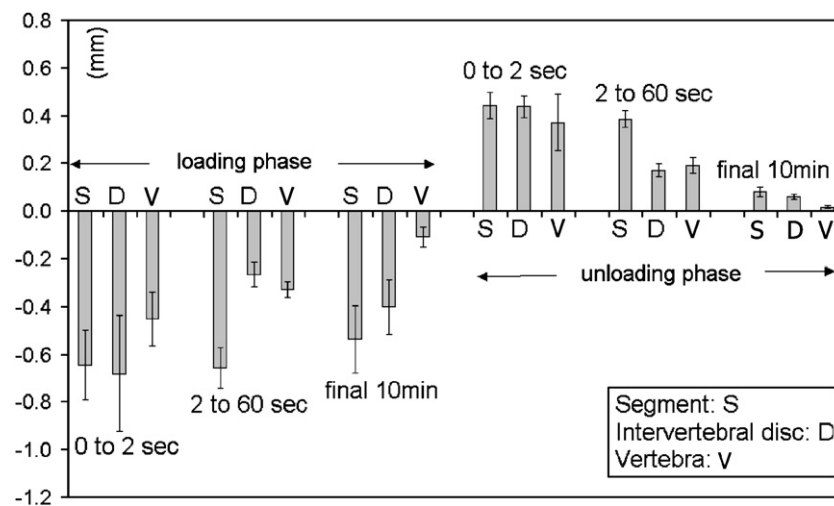


Fig. 4. The average height loss and recovery of segments, discs and vertebral bodies over intervals from 0 to 2 s, from 2 to 60 s and during the final 10 min of the loading and unloading phases. Error bars indicate standard deviations.



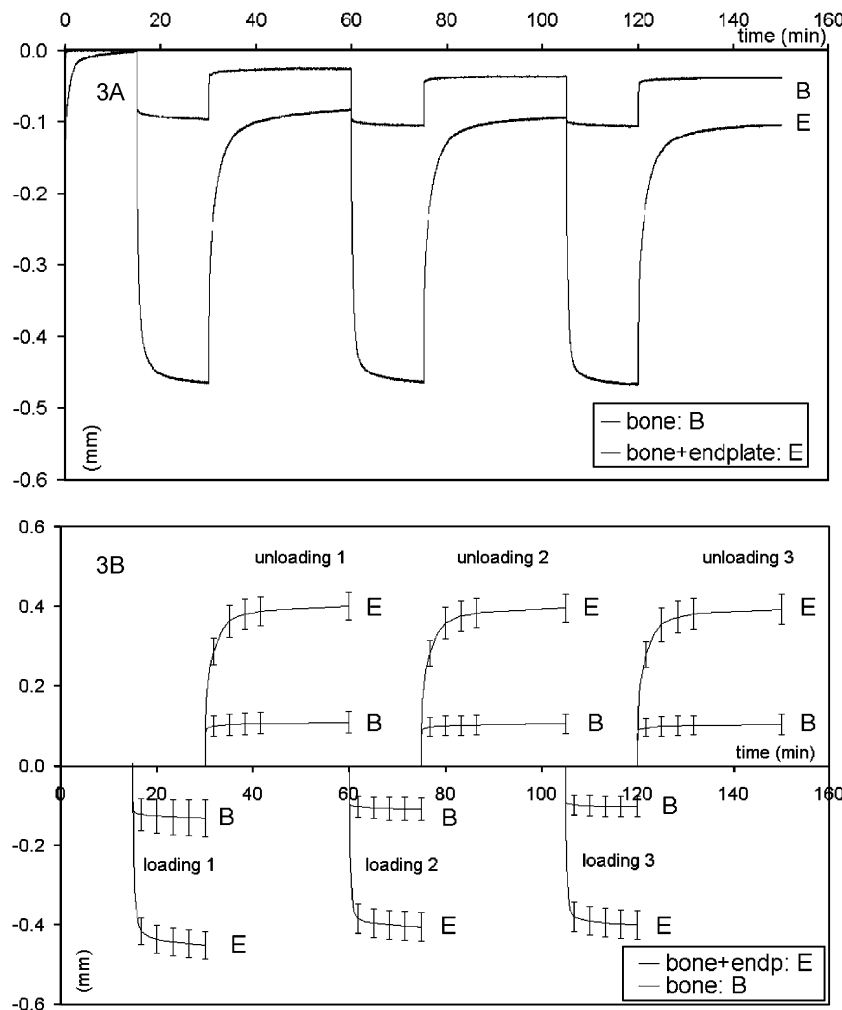


Fig. 5. (a) Typical example of a compression load applied to a 10 mm diameter bone cylinder with and without endplates showing the height change during three loading cycles. The sample without endplates was obtained from the full sample. Note the different scale compared to Fig. 3. (b) Average changes in specimen height of 10-mm bone cylinders with and without endplates (mean, SD) in each loading and unloading phase. Height was calculated relative to the height at the end of the previous (un)loading phase. The length of the sample with the endplates cut off was shorter than the sample with endplates still attached, the curve of the sample without endplates was corrected for this difference in height by multiplying the deformation with the ratio of the original sample heights and the sample height of with endplates cut off. Error bars indicate standard deviations

sample with the endplates attached was 29.9 mm (SD = 2.0 mm). The length after removal of the endplates was 18.9 mm (SD = 2.2). The thickness of the endplate of the bone plugs was measured; the average minimum value was 2.0 mm (0.3 mm SD). Fig. 3a shows the deformation of such cylinders over three loading cycles. The deformation during compression and unloading was time-dependent in both the groups (Fig. 5a).

The change of height of the sample with the endplates attached was, at the end of a loading cycle, about four times larger than without endplates (Fig. 5a,  $p < 0.001$ ). The loss of height per loading cycle was also larger for samples with the endplates attached ( $p < 0.004$ ). The loss of height per loading cycle decreased for all samples during the second and third loading cycle, in comparison to the first cycle ( $p < 0.008$ ).

The deformation was calculated relative to the displacements at the end of the previous phase (Fig. 5b), this

value was corrected for differences in sample length. The average deformation of the samples with endplates was, at the end of the loading phase, also four times larger than the average deformation of the bone samples (Fig. 5;  $p < 0.001$ ). Similarly to the tests on vertebral bodies, discs and motions segments, the recovery phases of all three cycles were virtually identical. The overall loss of height in the second and third loading cycle was almost zero. The overall loss of specimen height during the test can, therefore, be attributed to the first loading cycle.

The creep of both cylindrical samples decreased considerably over time (Fig. 6). The change of load was applied during the first 2 s of each loading phase. After this early phase, the creep of the samples with endplates was approximately five times larger than that of the samples without endplates ( $p < 0.001$ , Fig. 6). During the final 10 min of each phase the deformation in both groups was

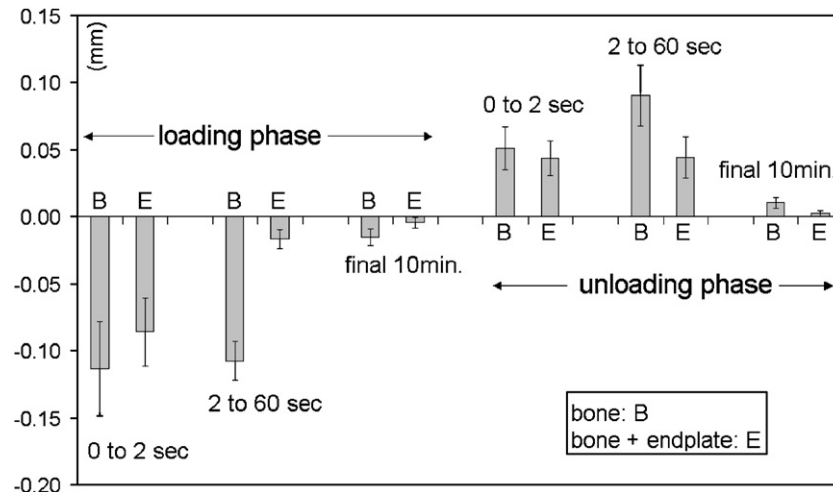


Fig. 6. The average change of specimen height of the 10 mm cylindrical specimen of a vertebra and of the same specimen with the endplates removed. Height changes were calculated in the interval from 0 to 2 s, from 2 to 60 s and during the final 10 min. Error bars indicate standard deviation.

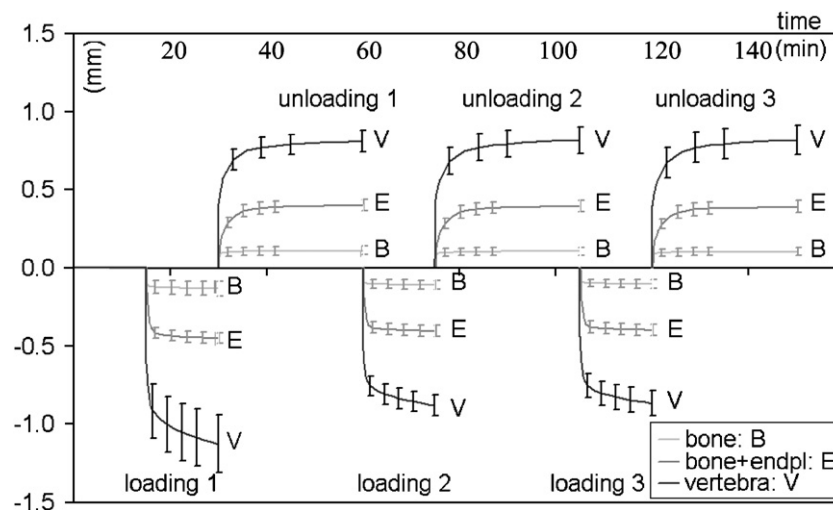


Fig. 7. Average change in specimen height for bone, bone including adjacent endplates and single vertebra. Error bars indicate standard deviations.

small, but a significant difference between bone and bone + endplate persisted ( $p < 0.001$ , Fig. 6).

Fig. 7 shows that creep of the vertebral bodies (V) from the first test was twice as large as creep of the cylindrical bone samples with the endplates attached (E, second test), which was in turn four times larger than creep of the sample without endplates ( $p < 0.001$ ).

#### 4. Discussion

The mechanical behavior of a motion segment during axial compression is complex. In the present study, we showed that time-dependent deformation of the disc, the endplates and the bone all contribute to the deformation of a motion segment in a prolonged and repeated compression test. However, in the present test it is not possible to

discriminate between the creep of structures within the endplate. Most likely, the hyaline cartilage endplate, the bony endplate as well as the epiphyseal growth plate contribute to the creep.

Each loading or unloading phase can be divided into three distinct phases: The loading phase, the first 2 s in which the compression load increases or decreases to its desired test level (creep cannot be determined whilst the load changes), the early creep phase (the interval from 2 to 60 s) and the secondary creep phase (the interval from 60 s until the end of the loading or unloading phase).

During testing the endplate deforms and bulges into the vertebral body. The trabecular bone beneath the nucleus is compressed. However, the test on bone samples without endplates shows that creep of bone is already small during the early creep phase, suggesting that the bulging of the

endplate into the vertebral body occurred mainly during the loading phase. This is in line with tests on human motion segments by [Holmes and Hukins \(1993\)](#) who measured an instantaneous displacement of the endplate into the vertebral body of 0.14 mm during compression tests at 1600 N, followed by a further creep of only 0.023 mm.

During the early creep phase, the deformation of the intervertebral disc was comparable to the creep of the vertebral body. The creep of the motion segment, however, was twice as large. This effect was seen both in loading and unloading. An explanation for the difference in the early response of a segment and an intervertebral disc can be given by the composition of the tested specimens. The vertebral body and the intervertebral disc contained two endplates each, whilst the motion segment contained four endplates. The test on the cylindrical samples showed that creep in samples with endplates was much larger than creep of the identical samples with the endplates removed. Thus, creep of the bone was small as compared to that of the endplate; the endplate was more deformable than trabecular bone. In the test on motion segments, four endplates were present. The influence of these endplates in the deformation of the motion segment was therefore also large. Besides visco-elastic the disc is poro-elastic. The role of fluid flow in the mechanical behavior of the disc is also time dependent. Rapid fluid flow, due to mechanical loading, affects the periphery of the disc whilst long-term loading affects all regions of the disc ([McMillan et al., 1996](#)). Fluid flow from the nucleus is a slow process compared to visco-elastic deformation. Creep of a motion segment is by nature a combined visco- and poro-elastic process. These processes work coincide from the beginning of the test. However, we assume that the duration of the early phase was too short for a large influence of fluid flow from the nucleus and that the endplates play a large role in the deformation during the early creep phase.

After the early creep phase, the behavior of the intervertebral disc started to follow the pattern of the motion segment, whilst the creep of the vertebral body fell behind. Comparing tests of samples containing an intervertebral disc and tests on samples without, results show that creep of both bone and endplates was small compared to that of segment and disc. The effect of the endplate apparently decreased. This suggests that the intervertebral disc determines the late creep phase, probably through fluid loss from the nucleus and through visco-elastic creep of the annulus fibers.

Lumbar vertebral bodies and the cylindrical samples of the thoracolumbar region with the endplates still attached showed comparable mechanical behavior under mechanical loading. However, the change of height of the vertebral body was approximately twice as large ([Fig. 7](#)). It is not to be expected that the properties of the lowest thoracic vertebral body differ substantially from those of lumbar vertebral bodies. The larger height loss of the vertebral bodies can probably be explained by the differences in the

thickness of the endplate samples. The cylindrical sample was machined from the center of the vertebral body. The thickness of the endplate in the center of the disc is smaller than the thickness of the endplate under the annulus ([Fig. 1](#)). The endplate plays an important role in creep. Due to endplate thickness, the creep can be expected to be larger for a complete vertebral body.

Another difference between vertebral bodies and the bone plug is the presence or absence of a cortical shell. However, tests on cylindrical samples showed a very small deformation of vertebral bone during the creep phase. The effect of the presence of cortical bone, a changed stress level due to load bearing of the cortical shell, therefore will also be small.

In a segment, besides being compressed, the endplates bulge into the vertebral body. Pressure measurements in the intervertebral disc show that the compressive load in a healthy disc decreases towards the periphery ([Adams et al., 1996a](#)). This leads to higher loads in the center of the vertebral body. The trabecular bone of the vertebral body carries this load, which locally leads to a higher deformation. In the present study, deformation of the endplate contributed substantially to the deformation of the segment. This may not be the same in degenerated discs. Degeneration is typically a problem of the mature human spine. In contrast to the animal model, the vertebral growth plates in adult human spines have closed in their early twenties ([Albert and Maples, 1995](#)). Thinning of the endplate is observed with aging ([Ferguson and Steffen, 2003](#)) and the loading profile within the intervertebral disc also changes with aging ([Adams et al., 1996b](#)). Bulging of the disc into the vertebral body may therefore be less pronounced in degenerated segments than in young porcine segments. The present in vitro tests will, therefore, only reflect the mechanical behavior of a disc at the equivalent age in human life. The effect of the above, changes in disc and endplate properties, on creep behavior deserve a separate study.

The porcine disc is, both functionally and anatomically, an accepted model for mechanical testing of the spine. The heights of human and porcine vertebral bodies, measured at L4, are very similar ([McLain et al., 2002](#)). The main difference between adult human and immature porcine vertebra, with respect to morphology, is the area of the vertebral body ([McLain et al., 2002](#)). We therefore applied a load based on the area of the individual porcine disc to attain pressures comparable to those on human discs in daily life ([Wilke et al., 1999](#)). The average compression load during the loading phase in the present experiments corresponded to two times body weight of the animal; this is well below the compression strength of the spine.

Tests on immature porcine ([Bass et al., 1997](#)) and human intervertebral discs ([Dhillon et al., 2001](#)) showed that freezing influences creep behavior of porcine discs, while creep behavior of human discs was not altered. The change in porcine samples was largely attributed to changes in swelling pressure and permeability of the disc. Due to



preparation of the samples, the number of samples to be tested and testing time, the use of fresh samples was undesirable. In the present study, all groups were frozen and thawed before testing. Therefore a comparison between groups is allowed.

In the present study, we have investigated how deformations of the disc, the endplates and the vertebral body contribute to the deformation of a motion segment in a compression test. We showed that the endplate contributes significantly to the creep of a single vertebra and that the vertebral body contributes to the creep of a segment. Creep deformation of a complete motion segment is thus determined by the behavior of the bone, the endplates, the annulus and the nucleus. Each part has a separate time scale. Creep of bone is present during the early creep phase; however, it is small compared to creep of the endplate. Creep of the endplate was substantial during the early creep phase and finally creep of soft tissue of nucleus and annulus dominates the late creep phase.

If the effect of remaining endplates in a compression test is not taken into account, the contribution of the segment to the deformation of the spine will be overestimated. Tests on motion segments should preferably be performed on a segment with the outer endplates cut-off.

### Conflict of interest

This study has not been published or submitted to publication elsewhere. All authors hereby state that they have been involved in the design of the study, interpretation of the data, and writing of the manuscript. All authors have read and concur with the content in the manuscript. We have not received funding for this project.

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